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Fusion Welding of 2014 Aluminum Alloy

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Engineering Laboratories

Bell Laboratory Report

BLR 61-41 (M)

Revision A

FUSION WELDING OF 2014 ALUMINUM ALLOY

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I. INTRODUCTION

In a search for stronger alloys, several aircraft companies turned to 2024 and 2014. Both have an ultimate strength of nearly 70,000 psi and are similar in that both depend mainly on copper for their strength. North American Aviation (Ref. 1) chose 2024 for their large Navaho tanks, whereas Martin selected 2014 for Titan tanks of about the same size. The 2014 is considered to be somewhat less crack sensitive so it was chosen of the two for our investigation.

After the above-named alloys were adopted, Alcoa was approached by an aerospace industry group with the request that Alcoa develop a weldable high-strength aluminum alloy (Ref. 2 and Ref. 3). The result was their 2219 alloy which indeed does have weldability approaching that of 6061 along with a tensile strength, 62,000 psi, approaching 2014. Boeing is using it on their Bomarc tanks, (Ref. 4) and our Metallurgy Group plans to investigate it in a continuation of this program.

Both 2014 and 2024, it should be noted, are generally classed as not weldable (other than by resistance welding). To weld them requires refined techniques and close control of variables. Customarily, these alloys, when fusion welded, are used in the as-welded condition and, in recognition that the joint will be about half as strong as the parent metal, the designers arrange to have the joint about twice as thick as the parent metal. This is customarily done by thinning most of the surface of the tank skins or segments before welding so that only a band of original thickness material about two inches remains alongside each joint to be welded. The removal of material to produce the large thin regions is done by mechanical milling or by chem-milling (a patented chemical etching process).

2014 has a high susceptibility to stress corrosion cracking and has only a fairly good general corrosion resistance compared to 6061. Therefore the use of alclad 2014 is often required. In the performance of 2014 welds, the main problems are inconsistent ductility and strength and occurrence of fine porosity. Machine-made welds are reasonably free of cracking trouble, but manual welds, especially repair welds, present a serious cracking problem.

This report will describe the investigation of the welding of 2014 alloy. The objectives were to get at least some tentative answers to the problems noted above and to determine typical properties obtainable through several combinations of preweld and post-weld heat treatments.

A principal objective, for example, was to study the weld-then-age sequence since this had proved so very successful at Bell on 6061-T4, allowing nearly full base metal strength to be realized in 6061-T4 joints which were only aged after welding, eliminating the often-difficult step of solution heat treating.

The welding reported here was done by the inert-gas-shielded tungsten arc process (Heliarc), principally with mechanical equipment, although some hand welding was done. The material was 1/8 inch 2014 Alclad sheet.

II. CONCLUSIONS

No problems were experienced in making sound welds in 2014 alloy plates under laboratory conditions. Production and repair difficulties can be expected but these can be evaluated only on samples which would simulate manufacturing conditions.

The poor weldability of 2014 as compared to 6061 is attributed largely to its wide melting range of 230 F versus 105 F for 6061. The effect is to delay solidification of the base metal at the edge of the weld. While it is in this partially-melted condition, it has low strength and ductility and is subject to cracking from shrinkage stresses.

Hardness surveys across the joints were very useful in determining the relative strengths of the weld and the heat-affected zones in the base metal.

Stress corrosion tests showed that joints aged after welding cracked in 160 hours in a moist salt atmosphere. Joints in the as-welded condition did not crack during the 291-hour test. There are strong indications that fusion welded 2014 should be used only in the as-welded condition.

All joints failed in the weld metal in both tensile and bend tests. This was not attributable to any specific fault other than that the weld was simply too soft for the alloy being joined. On fully heat-treated joints, the weld hardened to where it approached the base metal strength; i.e. 89 per cent of the 70,000 psi base metal strength.

Hydrostatic bulge tests in which a disc is loaded biaxially will simulate the stresses found in a pressure vessel much better than uniaxial tensile and bend specimens. So far 2014 has not performed better than 6061. The indication is that weld joint stresses will have to be kept at moderate levels to assure reliability.

In studying the effect of welding speed on the strength of welded-then-aged 2014-T4, we found that an increase in speed improved the response to aging in the heat affected zone just as it does in 6061-T4. A similar effect occurred in both alloys in that speeds above 15 ipm did not bring significantly greater improvement in HAZ hardenability.

III. METALLURGY AND HEAT TREATMENT

The 2014 alloy is of the aluminum-copper-magnesium-silicon type employing copper aluminide ($CuAl_2$) as the primary precipitation-hardening agent. A secondary precipitation hardener, Cu Mg_5 Si_4Al_4, greatly increases the strength attainable through artificial aging and is also responsible for the natural aging characteristics of this alloy.

The secondary alloying elements, that is, magnesium and silicon form low melting complex eutectics with melting points of 960-980 F. These limit the solution heat treatment to 945 F, above which there is melting of the eutectics with danger of cracking as well as permanent harm to mechanical properties, especially ductility.

Complete re-solution of the $CuAl_2$ micro constituent cannot occur at 945 F so there is always an excess of this present. The form and distribution of the $CuAl_2$ influences the ductility and toughness of the alloy. In unwelded sheet metal the excess constituents are evenly distributed in small more-or-less globular shapes. After welding, these constituents exist as long strings and films within the structure of each grain in the weld. In this condition they tend to form continuous brittle planes of weakness. In the overheated base metal at the edge of the weld there is likewise a grain coarsening with formation of the brittle films.

The chemical composition limits for 2014 are as follows:

Element	Min %	Max %
Copper	3.9	5.0
Silicon	0.5	1.2
Iron		1.0
Manganese	0.40	1.2
Magnesium	0.20	0.80
Chromium		0.10
Zinc		0.25
Titanium		0.15
Aluminum	remainder	

The 2014 alloy is hardenable by a precipitation heat treatment. This is in two steps: the first, called solution heat treatment consists of heating to 940 F to dissolve the $CuAl_2$ and certain other microconstituents and then quenching rapidly in water. This produces the 2014-T4 condition. The quench is fast enough that there is not time for the constituents to precipitate out in accordance with their decreasing solubility at lower temperatures. The -T4 material is stable at room temperature. The second step of the heat treatment is called aging (or artificial aging) and consists of heating the -T4 at 340 F for 10 hours. This gives the strong -T6 condition. The strengthening results from precipitation of submicroscopic particles of the hardening constituents. When heated to higher temperature "overaging" results with loss of properties. Finally, heating to around 800 F gives gross precipitation and the soft stable "annealed" condition.

IV. WELD METALLURGY AND WELDABILITY

Aluminum alloys melt over a range rather than at a single temperature and the relative difficulty of welding any alloy can be estimated from this range. An alloy is without strength or ductility while it is in its melting range and a broad range implies a long time in which the material alongside the weld is in a condition in which shrinkage stresses easily produce cracks. In the table below the relatively poor position of 2014 explains its crack sensitivity, especially in manual welds which are characterised by slow speeds and high heat inputs. The weldability rating is purely arbitrary.

Alloy	Melting Range F	Difference F	Weldability Rating
1100	1190 - 1215	25	1
6061	1100 - 1204	105	2
2219	1000 - 1180	180	2
2014	950 - 1180	230	4
2024	935 - 1180	245	5
7075	890 - 1180	290	6
4043	1065 - 1170	105	(filler metal)

The second factor influencing weldability is the solidus temperature (or bottom of the melting range). Ideally, the weld metal should solidify after the adjacent base metal has solidified so the welding shrinkage strains could be fed or filled up by the still-molten pool of weld metal. With 4043 filler on 6061, this holds true, but on 2014 there is no filler metal with so low a solidus as 2014. The most crack-free filler for 2014 is 4043 and its solidus is 100 F above that of the base metal. It might appear that the weld would be solid long before the base metal and that cracks in the latter were inevitable. This does not occur, only because of the continual progression of the weld pool and the exceedingly steep thermal gradients across the weld and base metal.

In the wrought base metal before it is exposed to welding, the excess of $CuAl_2$ and other microconstituents is evenly distributed in small more-or-less globular shapes. Their effect, even though they are brittle, is not serious. However, in the process of welding, the microconstituents in the fusion zone assume a different configuration. They, of course, melt along with the aluminum matrix in the arc path where the weld is being made. After introduction of weld filler rod, the weld solidifies in what is no longer a wrought structure but instead is a cast structure consisting of fine elongated grains, all oriented in the direction of solidification of the weld pool and pointing generally toward the centerline of the weld. Now the microconstituents assume the shape of long parallel strings and films within the dendritic structure of each grain. In this condition a brittle constituent becomes more harmful because it comes more closely to forming a continuous plane of weakness in the joint.

The grain size and the size of the fine dendrites within the grain can be lessened by welding at low heat inputs, that is, at a high welding speed. This promotes rapid solidification of the weld pool. Grain refining additives in the filler metal also can help. In the finer grain, not only are the constituents less likely to form solid continuous films, but also being smaller, they can be more completely dissolved in any subsequent heat treatment.

V. EXPERIMENTAL PROCEDURE

The material for the investigation was Alclad 2014-T6 sheet in 1/8 inch gage. This represented the thickest material contemplated for use in the immediate future. When the -T4 condition was needed, the 2014-T6 was solution heat treated (1 hour at 935 F and water quenched) to produce this. Welds were parallel to direction of rolling of the sheet so that tensile bars cut from this would be loaded transverse to direction of rolling.

The mechanized welding was done by the gas shielded tungsten arc process on Airco Automatic Heliweld equipment. Welding current was AC from a 400 ampere AC power supply having capacitors in the secondary circuit to give a balanced wave shape. The joints were square butt with zero to 0.010 inch gap. The edge of the joint on backside was broken, i.e., beveled very lightly, to improve the penetration bead and eliminate the underside centerline crevice.

Cleaning before welding consisted of a caustic dip followed by nitric acid, then water rinse. Immediately before welding, the abutting edges were filed with a clean Vixen file to give a bright surface.

The welding wire was 1/16 inch diameter type 4043 (5% silicon alloy). To insure surface cleanliness of this, a fresh stock of the Linde HQ grade was used. The initials HQ stand for High Quality and denote that it has a shaved finish of high luster and unusual cleanliness.

Welds were made in one pass usually at 20 ipm, but speeds from 5 to 25 ipm were investigated in order to determine the effect of speed on strength. The tungsten electrode was 1/8 inch diameter of 1% thoriated type.

The welding fixture had water-cooled copper hold downs and a mild steel backing bar. This bar had a flat groove .040 inch deep by 5/16 inch wide.

The welded panels were heat treated as necessary then cut into bend and tensile specimens. Samples for hardness surveys and metallurgical examination were also taken.

The tensile specimens had a 0.5 inch wide by 2.5 inch long reduced width section with the weld crossways of the specimen at the center. Weld reinforcement was ground flush on tensile and bend specimens. The latter were one inch wide by 6 inches long, bent around a 5T radius (1-1/4 inch diameter circle for 1/8 inch samples).

VI. TENSILE AND BEND TEST RESULTS

The tables of tensile test results show the average of three specimens; in the bend test two specimens were tested and both values are recorded.

The yield strength as reported is subject to error when determined on a specimen having zones of varying strength and ductility within the two-inch gage length upon which yield is based. When the weld is considerably softer than the base metal, it can be presumed that it is well past its yield strength by the time the stress reported in the table is reached. Where all zones are about of the same strength, this error is slight.

Table I gives the properties of Alclad 2014 base metal in several heat treatments and two orientations. Table II gives the properties of the welded joints. The same data is presented in the bar graph, Figure 1 giving perhaps a more rapidly comprehended picture of the strengths of the two welding methods (mechanical-and manual-inert arc) and the several heat treatments.

The minimum bend radius and bend angle required for satisfactory service performance is not known. The 5T bend radius was chosen because it is about the minimum to which some of the stronger joints could be bent. Since a bend angle of about 25 degrees is needed to form the weld and heat-affected zone around the mandrel, this was tentatively taken as the minimum acceptable bend angle. With those specimens having relatively soft welds there was trouble keeping the weld against the mandrel so that it would not lift and take a sharp bend radius of its own choosing. To correct this, we laid a strip of base metal under the specimen to help force it to conform during bending.

Assuming a 25 degree angle as the minimum, practically all the specimens passed except the 4A set. The only high ductility bends were in the as-welded ones.

The principal observations that might be made from an examination of the tables and the bar graph are summarized below. Certain of these are elaborated upon in later sections.

1) In the base metal the transverse properties are slightly poorer (0.5 per cent) than those taken longitudinal or lengthwise of the direction of rolling. All of our welds were oriented so the tensile bars were loaded transversely.

2) The 2014 did not perform nearly as efficiently as 6061 in a weld-and-age sequence. Joint efficiency with 2014 was about 70 per cent, compared to 100% with 6061. Since all failures were in the weld metal, th- some hope that an improvement in the weld can raise this efficien-

3) Fully heat treated machine welds in 2014 had a tensile strength almost 90% of that of the base metal. However, the low ductility of these gave poor results in the bend tests and bulge diaphragm tests. These two tests, especially the latter one, are a good test of the dependability of the joint in an end item such as a pressure vessel.

4) 2014 as compared to 6061, appears to be less sensitive to effect of welding speed on joint strength of welded and aged -T4 material. In other words, there was little improvement as the speed was raised. As will be shown later, this is mainly an inadequacy of the weld metal which is simply too weak at all speeds.

5) The principal weakness in a 2014 welded joint is in the weld metal. All samples failed in center or edge of the weld so this is where development work should be directed.

6) Practically all specimens passed the bend test, assuming a 25 degree bend angle to be the criterion.

TABLE I

Base Metal Properties

.125 Gage 2014 Alclad Aluminum

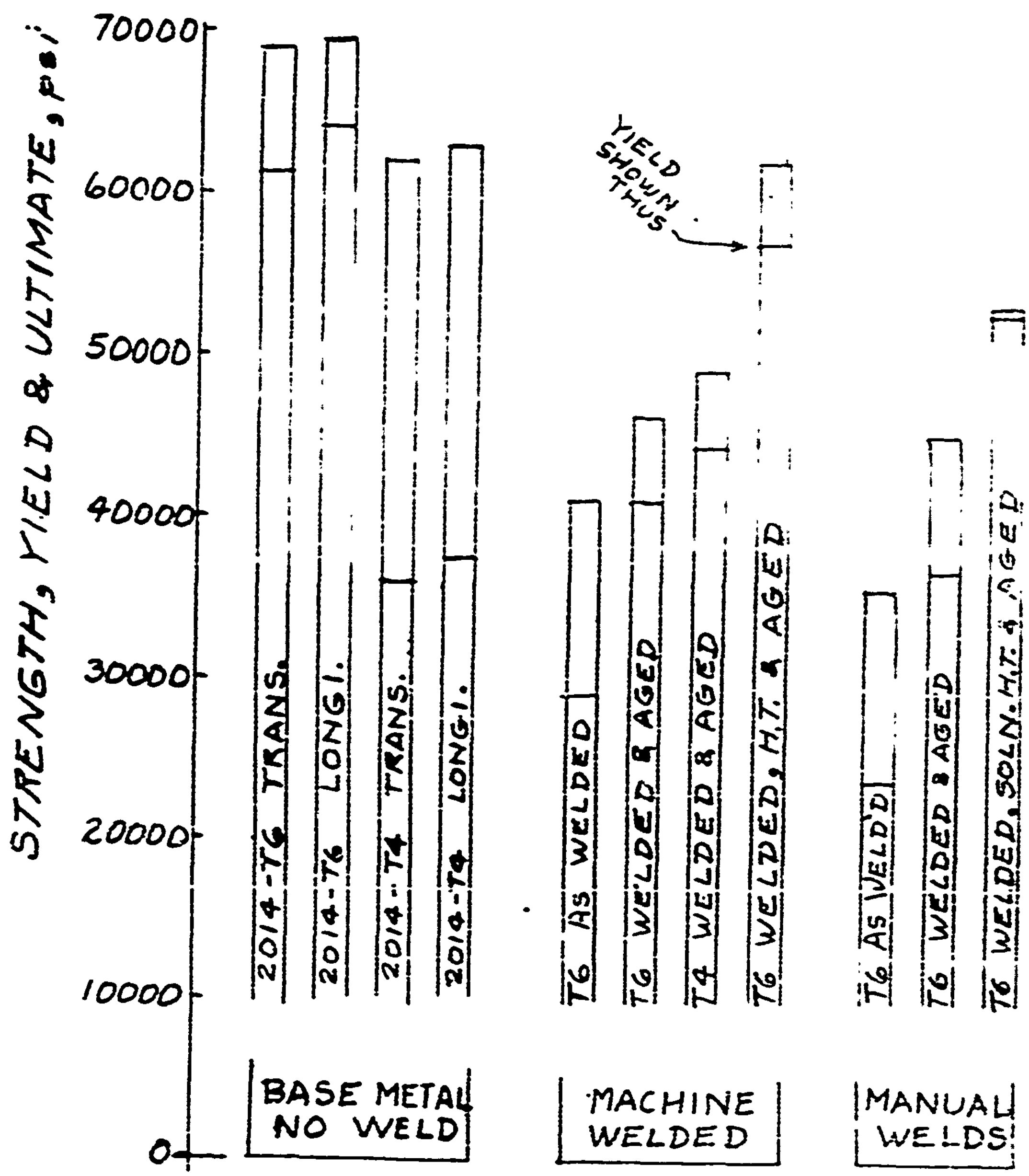
Condition	Grain	Tensile Strength	Yield Strength	% E in in
-T6, as received	transv	68960	61700	10
	longi	69240	64130	10
-T6, Soln. H.T. to -T4	transv	62350	36000	22
	longi	62800	37300	24
-T6, H.T. to -T4, and age to -T6	transv	71630	63700	11
	longi	72260	64300	11

TABLE II

Properties of Welded 2014 Alclad Aluminum

Code	Condition Before Weld	Treatment After Weld	Weld Speed	Tensile Strength	Yield Strength	% E in 2"	Fracture(1) Location	Bend Angle, Deg.
1A	T6	As welded	20	41000	29100	2.3	EW, EW, CW	40, 55
1B	T6	Aged	20	45600	40500	2	EW, EW, CW	25, 20
1C	T6	HT & Age to -T6	20	62000	56700	2	EW, EW, EW	24, 25
2A	T4	As welded	20	36700	23000	3	EW, EW	27, 59
2B	T4	Aged	20	48400	44100	1	CW, CW	23, 27
4A	T4	Aged	5	42600	39700	1	CW, CW, CW	20, 20
4B	T4	Aged	10	44300	41600	1	CW, CW, CW	27, 32
4C	T4	Aged	15	49700	42200	2	EW, EW, CW	32, 32
4D	T4	Aged	25	48700	43400	1	EW, EW, CW	32, 31
5A	T6	As welded	Manual	35800	23600	2	CW, CW, CW	35, 32
5B	T6	Aged	Manual	44900	36400	2	CW, CW, CW	23, 26
5C	T6	HT & Age to -T6	Manual	52900	52300	1	CW, CW, CW	24, 25

(1) EW denotes edge-of-weld; CW denotes center-of-weld.



SUMMARY OF TENSILE TESTS
ALCLAD 2014 FIG. 1

VII. PERFORMANCE OF THE WELD METAL

In this program all tensile and bend failures were in the weld metal, either at centerline or edge, so a study was made of the weld.

Invariably in 2014 and 2024 welding the weld is the weak link

The edge-of-weld failure was more typical than the centerline one. The fracture followed closely that interface on one side of which lay the coarse grained overheated base metal and on the other side of which was the weld metal itself.

Scattered porosity was found in cross-sections of the welds even though x-ray examination had revealed none. This tended to be grouped near the edge of the weld and was so very fine, only 0.001 to 0.002 inch diameter, that x-ray could not resolve it. The edge-of-weld failures tended to fail through this porosity and it can be assumed that its elimination would raise the weld strength a few per cent. It should be emphasized that the amount of porosity was slight. The presence of some porosity in welds made under laboratory conditions suggests that it might be even more troublesome in production. North American (Ref. 1) solved a severe porosity problem on 2024 by using a 2-pass weld, during the first pass of which they could see the porosity bubbling to the surface. Common practice of others is to weld in one pass unless the thickness requires several passes.

The weld filler metal was type 4043 (5% silicon - 95% aluminum). Experience of other investigators with other fillers has been disappointing. Pure aluminum (1100) cracks along the welds so badly as to be completely unuseable. On machine welds, 2014 filler can be used and is about 5 per cent stronger than 4043, but in manual welds it cracks badly (Ref. 4).

The welds in our tests were ground flush. A slight improvement would be realized if the reinforcement were left on. Our bulge disc samples did have the reinforcement and these had the same edge of weld failure as did the tensile bars.

Effort might well be spent on improving weld properties by searching for a stronger alloy and by promoting finer grain size through addition of grain refiners or by ultrasonic agitation of the pool. So far, however, no one has found a technique better than the popular one which shuns high weld strength and instead depends upon deliberately thickening the weld joint area so that the stresses are low across the joint and it in turn can be left in the soft and ductile condition. This practice places no limit on the amount of repair welding that can be done. It is very likely the most reliable approach. Users have found that welds which are in any condition other than as-welded are low in ductility and as a result are sensitive to notches from defects or from unavoidable stress concentrations.

VIII. PROPERTIES OF THE WELDED JOINT AS REVEALED BY HARDNESS SURVEYS

The insight into 6061 alloy welds on a similar program several years ago was gained largely through use of hardness surveys. Hardness is closely related to tensile strength and a well-made survey will reveal the approximate strength of each of the several zones associated with a weld. A tensile test, on the other hand, determines the strength only of the weakest zone.

All the specimens of this test failed in the weld; the heat affected zones, being stronger than the weld, had no bearing on the results. However, should a stronger weld metal be developed, these zones could become of significance in determining the joint strength.

Several distinct zones exist in a welded joint in a heat-treatable aluminum alloy. These are shown in Figure 2 along with a typical hardness survey. The approximate temperatures at the limits of the zones are given; these are based on our work on 6061 (Ref. 6). Features of the zones are as follows:

1) Weld or fusion zone (1200 F). This is a fine grained casting composed of base metal plus filler metal. It is heat-treatable but not so well as the parent metal. In a machine-made weld it has cooled fast enough to be in a supersaturated (-T4) condition and is susceptible to hardening by aging.

2) Overheated zone (1100 F). In this narrow base metal zone the microconstituents have melted and agglomerated into coarse networks. This has low ductility and high susceptibility to stress corrosion. In manual welds this zone becomes wide and is the source of cracks.

3) The solution zone (1100-850 F). This has cooled rapidly from optimum temperatures (assuming it to be a machine weld) and is susceptible to aging to nearly full base metal strength.

4) Overaged zone (850-550 F). The cooling rate and maximum temperature are less than optimum so it will not age to full base metal strength. In manual welds this zone may be so soft as to have annealed properties; however, full reheat treatment practically erases this weakness.

5) Unaffected Base Metal (below 550 F).

Hardness surveys were made with the Rockwell B scale (1/16 inch ball, 100 Kg load) and were taken on the cross-section of the sample rather than on the surface. This avoided the need to file off the cladding.

The use of a hardness survey to study heat effects is illustrated in Figure 3. This is for 2014-T4, the left curve is for the as-welded joint; the right for a welded-and-aged one. The latter illustrates the zones described earlier. Tensile strength is annoted at certain points. The softness of the

weld metal, especially as-welded, is apparent. Upon aging it does harden, but not enough to match the rate of hardening of the base metal. The overaged zone is seen in the right curve when it dips to B72. This is somewhat more severe than the dip for 6061 at this speed. This was expected since 2014 is more sensitive to rate of quench than is 6061.

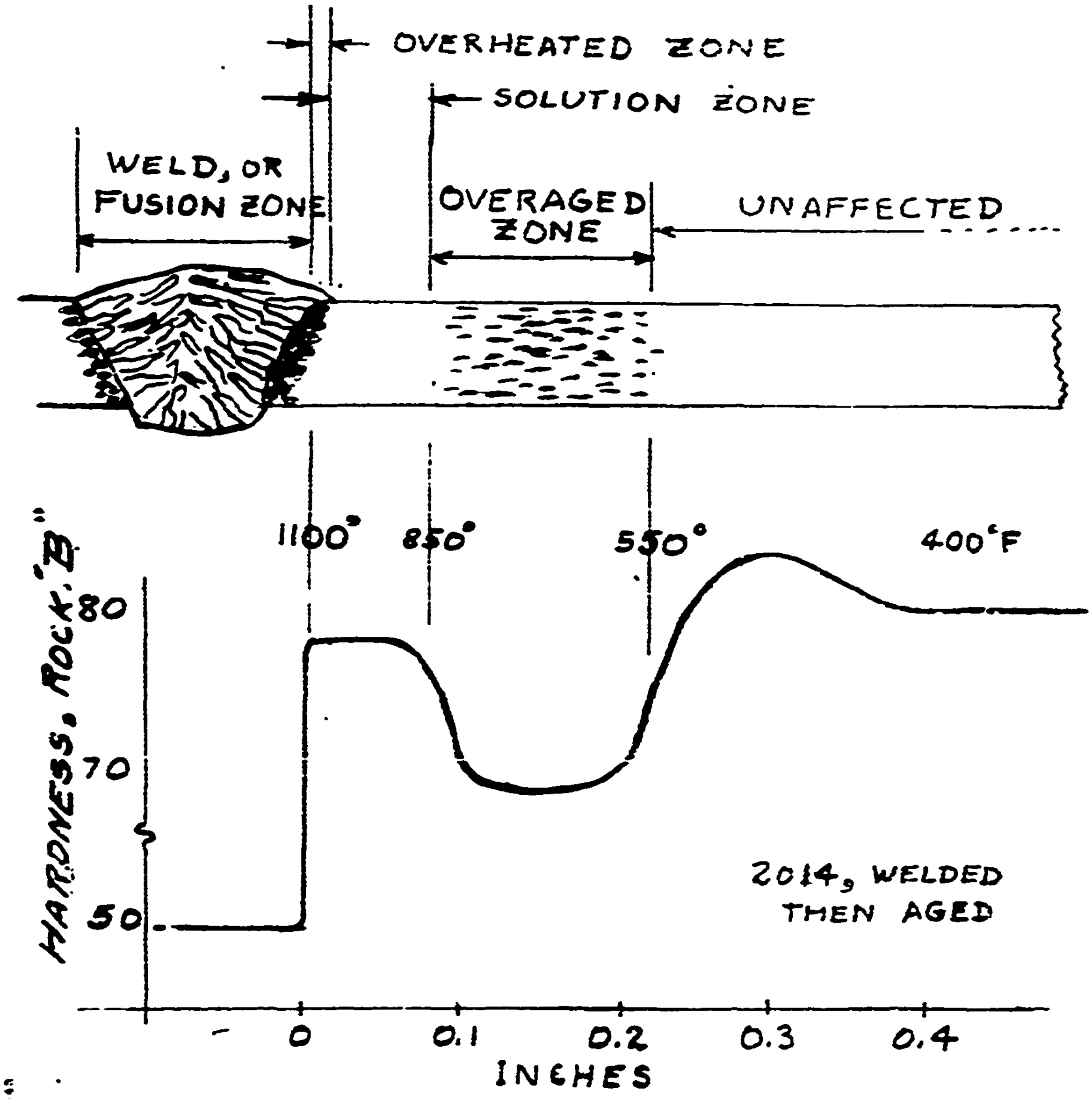
We consider the weld-and-age sequence, as illustrated in the preceding Figure, important because it proved invaluable on our 6061-T4 tanks. There a full heat treatment (quench and age) after welding was impractical for distortion reasons, but nearly -T6 strength was obtained through aging only and it was hoped that this could be duplicated with 2014 alloy. The effect of various welding speeds is discussed in another section of this report.

A study of 2014-T6 in three conditions of heat treatment after welding is shown in Figure 4. All failed in the weld in tensile tests at the values noted on the curve.

The low strength of the weld metal, even when aged is again evident. A full reheat treatment of the joint (curve 1C) however, brings the weld at least into the vicinity of the base metal strength. Probably the solution heat treatment benefits the weld by homogenizing it and refining the grain.

The center curve indicates that the weld was nearly as strong as the soft zone of the base metal and a slight improvement in weld strength might force the fracture to occur in the heat affected zone.

The fully heat-treated joint (1C) still shows some drop in the heat-affected zone where apparently some permanent deterioration was produced in the microconstituents by welding.



THE HEAT-AFFECTED ZONES WITH APPROX. THERMAL GRADIENT & HARDNESS SURVEY.

FIG. 2

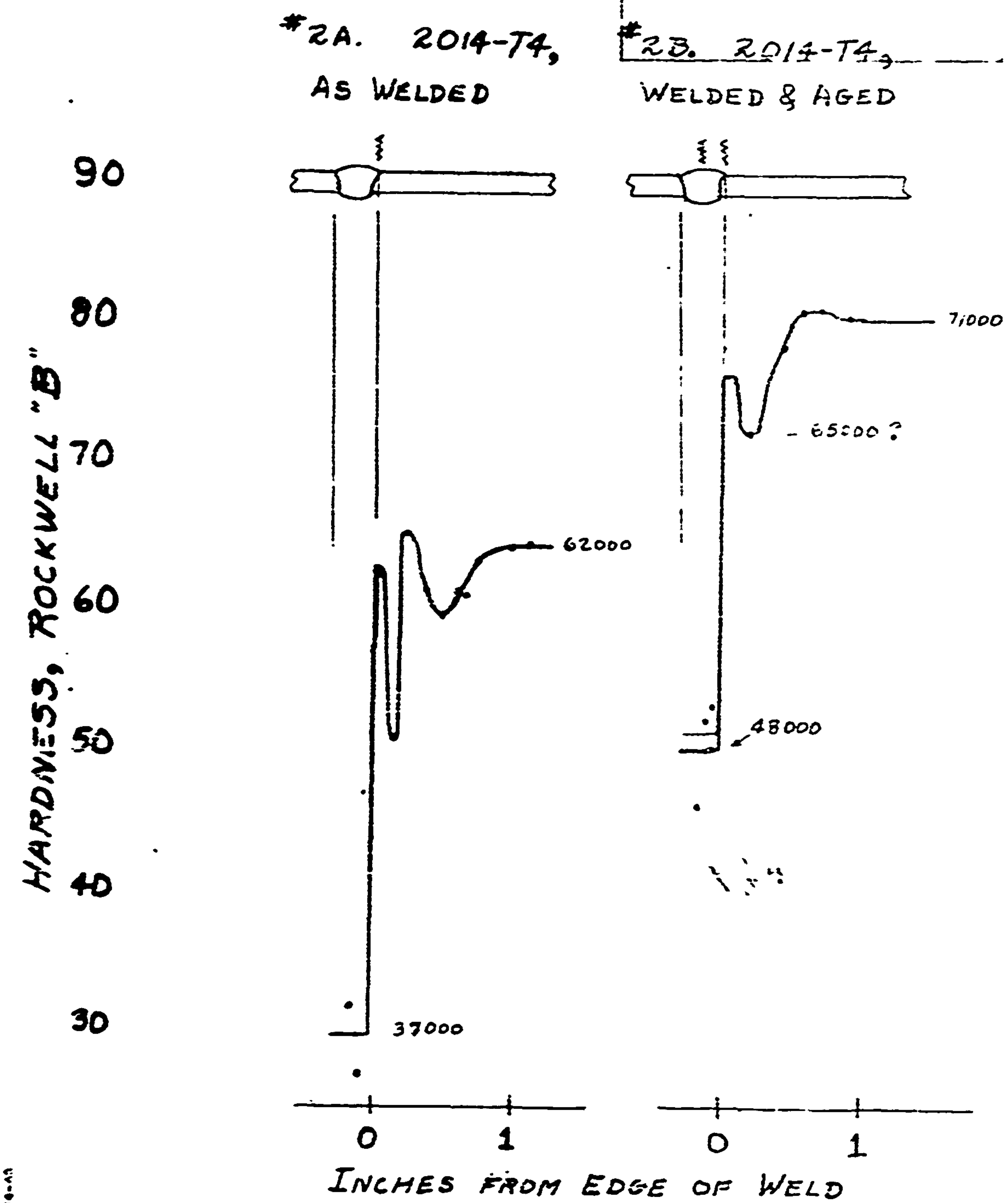
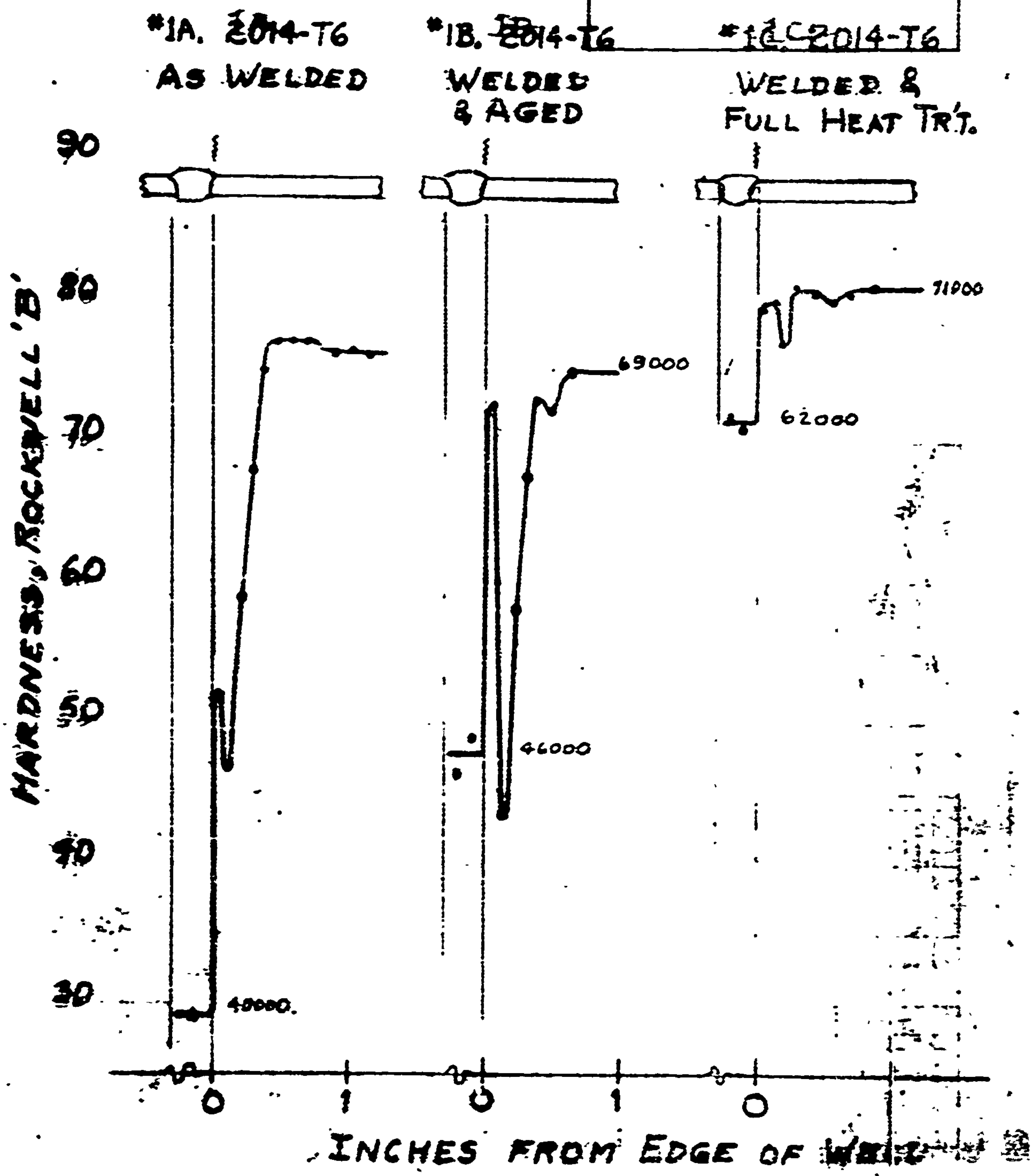


FIG. 3. HARDNESS SURVEY
2014-T4 WELDED AT 20 ipm
THEN TREATED AS SHOWN.

FIG. 3



2014-T6 WELDED AT 20 IPM, THEN TREATED AS SHOWN.

FIG 4

IX. THE EFFECT OF WELDING SPEED ON JOINT STRENGTH

Earlier in this report we have mentioned the success at Bell in welding 6061-T4 rapidly enough to assure that the heat-affected zone would still be susceptible to aging so it would reach full -T6 strength upon aging. Also, in the section on Tensile Results, it was noted that in our current experiments on 2014-T4 we tried various welding speeds but that consistent failures in the weld hid any relationship between speed and heat-affected zone strength. By means of hardness surveys, however, we can show this relationship.

Therefore, we ran hardness surveys across the 2014-T4 joints which had been welded at speeds from 5 through 25 ipm and then artificially aged. These are shown in Figure 5. The improvement in the strength of the heat-affected zone as the speed is raised is evident. Next we converted the minimum heat-affected zone hardness of each curve to equivalent tensile strength in preparation for the next Figure.

In Figure 6 we show three curves of tensile strength of welded-and-aged alloys plotted against welding speed. The bottom one is the historic one (Ref. 6) for 6061, and since all those failures were in the HAZ we label it "6061 Heat Affected Zones." The center curve is from our current data on tensile results and since all failures were in the weld we label it "2014 welds". The topmost curve plots the equivalent strengths of the heat-affected zones for 2014 from the preceding Figure so it is labelled "2014 heat-affected zones".

It is evident that an increase in welding speed improves the HAZ response to aging of 2014-T4 just as it does 6061-T4 and moreover for both alloys the rate of improvement diminishes sharply above 15 ipm welding speed. All that remains to be done is to devise a weld metal that will age to higher strengths than the HAZ, that is, to around 70,000 psi, and then the weld-then-age sequence can be used to advantage on 2014-T4. It is not likely that such a weld metal could be devised and if it were it might be too undependable to be practical. Aluminum welds stressed to 70,000 psi, when compared to those at 45,000 psi, would be far more sensitive to defects such as weld bead shape, micro-cracks, porosity, traces of oxide, and so on.

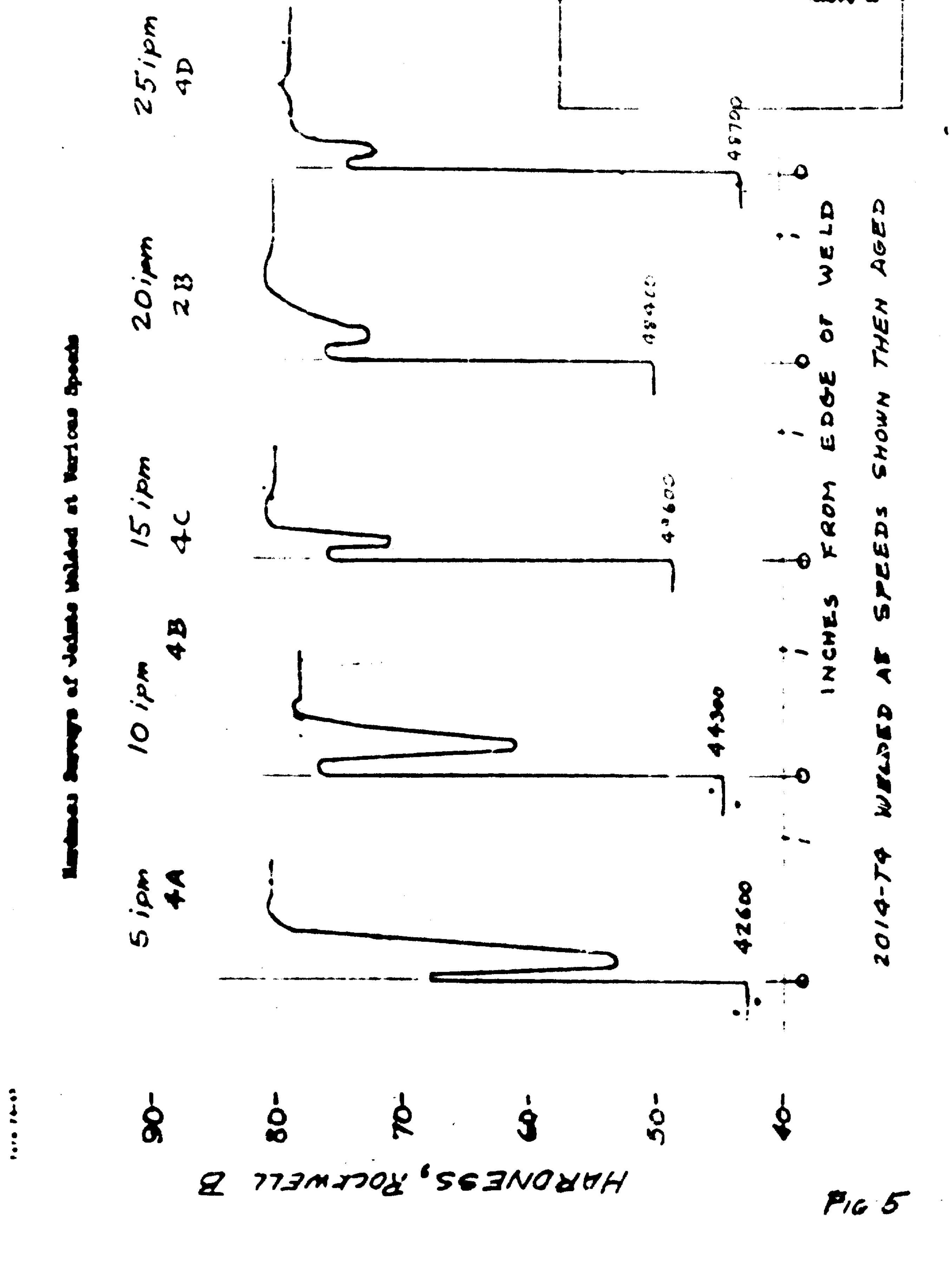

Hardness Surveys of Joints Welded at Various Speeds
5 ipm 4A
10 ipm 4B
15 ipm 4C
20 ipm 2B
25 ipm 4D
42600
44300
48600
48400
45700
90
80
70
60
50
40
HARDNESS, ROCKWELL B
0
INCHES FROM EDGE OF WELD
2014-T4 WELDED AT SPEEDS SHOWN THEN AGED

FIG 5

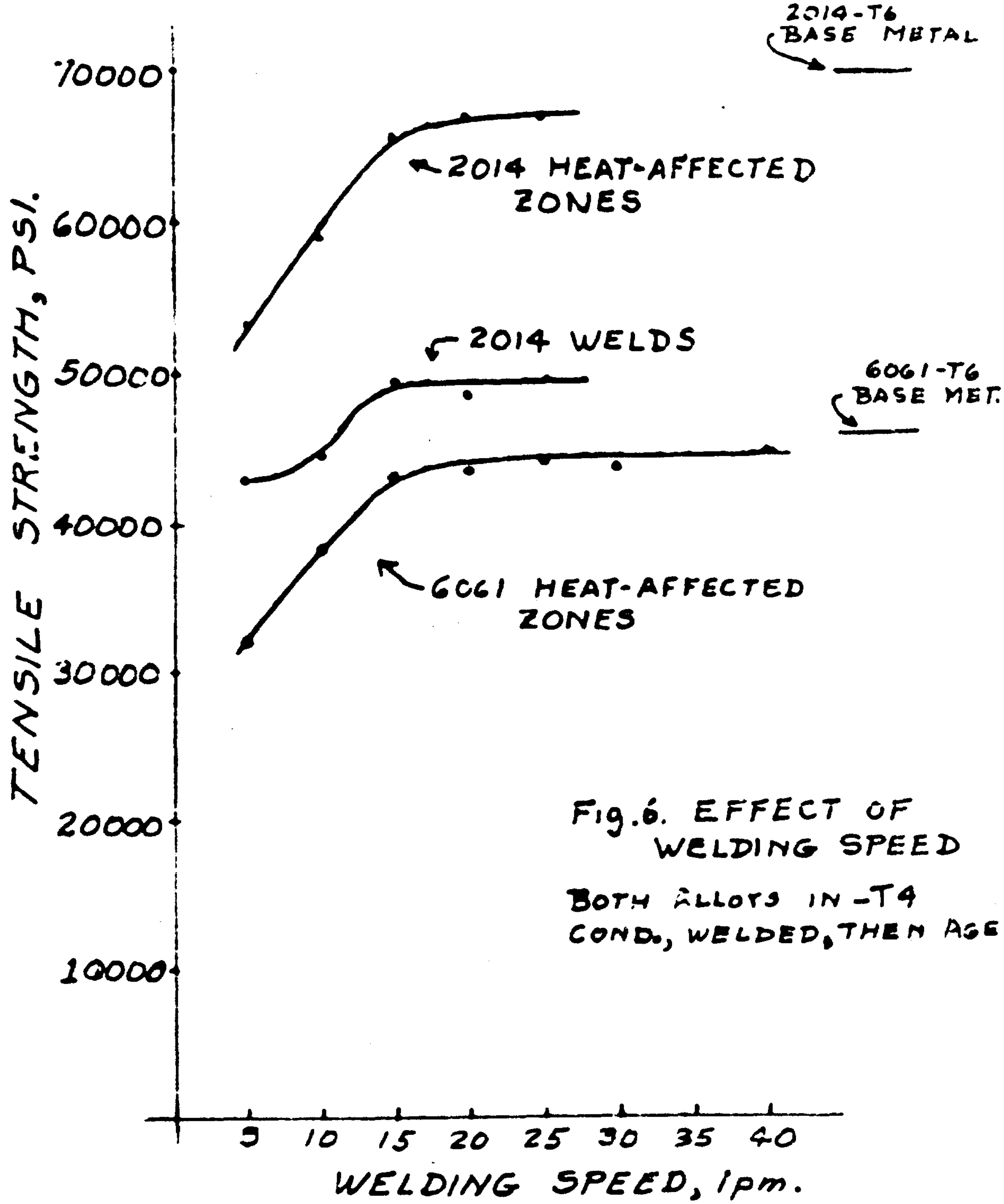


Fig.6. EFFECT OF WELDING SPEED

BOTH ALLOYS IN -T4 COND., WELDED, THEN AGED.

FIG. 6

I. STRESS CORROSION SUSCEPTIBILITY

Some metals, when under a high surface tensile stress and exposed to a corrosive medium, are likely to crack by what is termed stress corrosion. The crack penetrates along a very narrow path, usually following grain boundaries, and leaves little visible corrosion product on the surface. Cracking can occur in relatively mild solutions and in the relatively short time of several days or weeks. General surface corrosion or pitting may be entirely absent while the material is failing by stress corrosion. As stated above, the material must be under tension during the test and this is usually achieved by bowing it in a fixture.

The 2014 alloy is recognized as being susceptible to stress corrosion. The disposition of the $CuAl_2$ constituent appears to be the main factor. When it is in large agglomerations or in continuous films it is more harmful than when it is in solution or in a dispersion of fine globules. The first condition is found in material which is quenched too slowly in solution heat treatment or quenches from too high a temperature. Such conditions may be found in certain weld zones especially at the edge of the weld.

In stress corrosion tests the tester must choose an environment that he believes simulates service conditions and he must set a criterion of acceptable performance. Our tests were merely exploratory and used a conveniently available salt (sodium chloride) atmosphere at 100 F, 95 per cent relative humidity.

The samples were 1/8 x 1 x 8 inches in size with the weld across the center. Duplicates were clamped back-to-back with a 3/4 inch plastic spacer at the center and the ends pulled together by bolts, see Figure 1. According to the deflection formulas this should give a tensile stress of 50,000 psi on the outer surface near the weld.

The first tests were with the Alclad layer intact. Attack proceeded slowly and erratically from the raw edges of the specimen. Therefore, on the remainder of the tests the cladding was ground off. The cladding was continuous up to the edge of the weld, and even slightly within the bead. Probably it could be counted on to protect clad surfaces, but this affords no protection for raw edges or unclad members such as forgings.

As shown in the Table below, all samples in the as-welded condition lasted to the end of the test, 291 hours, without cracking.

All welds which had been aged after welding cracked and broke. One is shown in the photograph, Figure 7. Inadvertently, no test was made on samples fully heat treated after welding.

Those samples which cracked did so along the edge of the weld at the interface of the weld and base metal. Here the base metal has been heated to the welding temperature - about 1100 F - and the $CuAl_2$ is in the coarse stringy

condition which invites stress corrosion. These specimens had been aged and the result of this was that the matrix around the large $CuAl_2$ particles was hardened by the precipitation of sub-microscopic particles of several constituents including $CuAl_2$. This put the grains in a state of high internal strain and so raised the susceptibility to cracking.

The relative immunity of the as-welded samples was partly due to their low weld yield strength. This allowed them to yield plastically so that the surface stress was probably little higher than their yield strength, around 25,000 to 30,000 psi. These samples had a permanent set when removed from their clamping fixture.

Sample	Condition	Hours to Failure
1B	-T6 weld and aged	155
2B	-T4 weld and aged	179
1A	-T6 as welded	OK at 291
2A	-T4 as welded	OK at 291
5A	-T6 manual weld, as welded	OK at 291

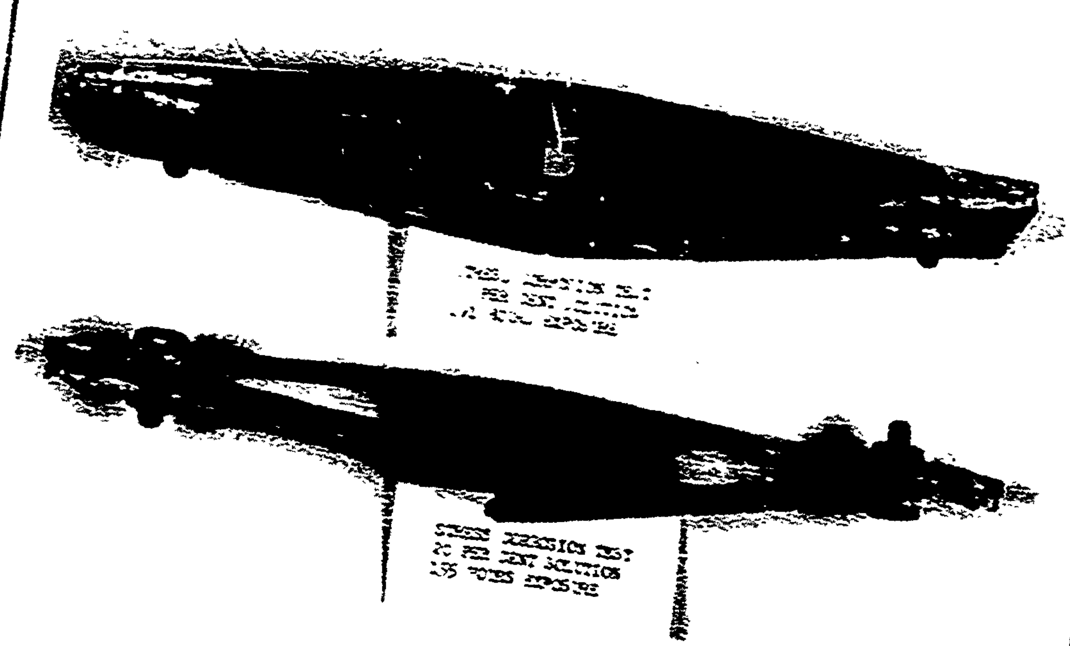


Figure 7. Stress Corrosion Specimens. Full size.

Each part is stressed by bowing around a plastic block. Both pairs are 2014-T6. The upper pair was in the as-welded condition and did not crack during the test. The lower pair was aged after welding and one cracked at 155 hours.

XI. REFERENCES

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